

Update on luminosity monitor and low- Q^2 tagger

Jaroslav Adam

BNL

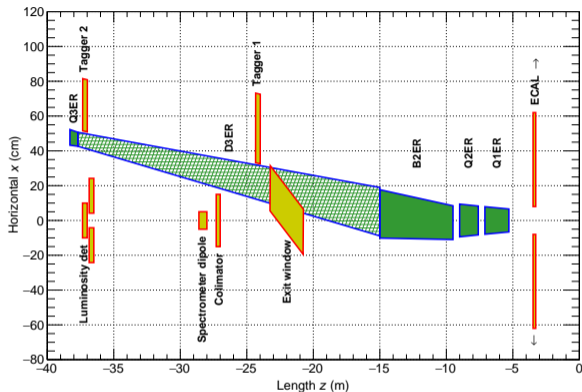
June 18, 2020

EIC Working Group

Outline

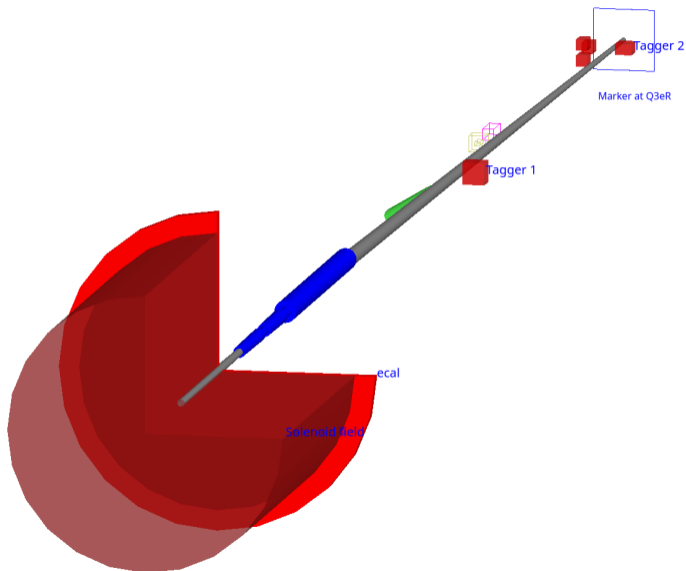
- Current results and issues with luminosity monitor and low- Q^2 tagger will be shown here
- Geant4 models is getting more complete
- Realistic implementation of beam angular divergence and vertex spread in event generators
- Possibility of two tagger detectors and connection to backward ECAL
- Geometry model for luminosity spectrometer as a fast approximation to get the acceptance
- Demanding requirements to select the detector technology

IR layout, electron outgoing side



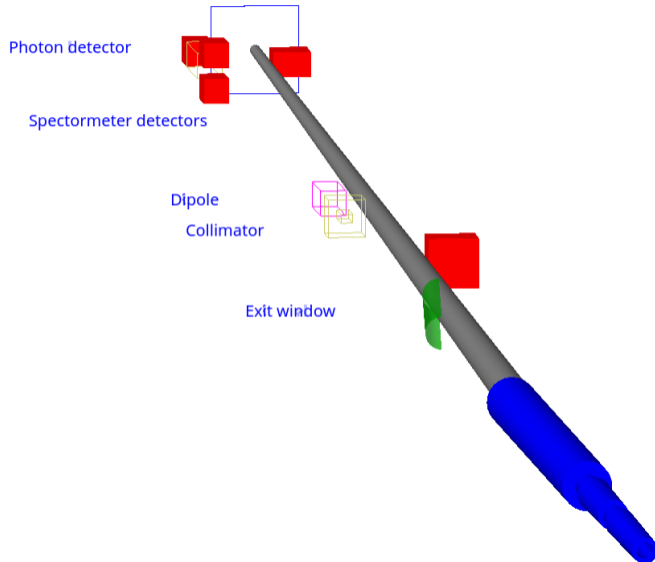
- Luminosity photons come along z to the exit window
- Scattered electrons are measured by ECAL and tagger 1 and 2
- All components shown here are implemented in Geant4 model, with D3ER drift space transparent

Geant4 model for electron-outgoing IR, tagger side



- Drift spaces in grey are transparent to all particles
- Tagger 1,2 and ECAL detectors mark hits by incoming particles
- Solenoid field uses the BeAST parametrization
- Beam magnets are shown in blue
- The ECAL is placed at $z = -3.28$ m, tagger 1 and 2 at $z = -24$ m and -37 m respectively
- Rapidity of ECAL is $-4.4 < \eta < -1.0$, very optimistic scenario
- The layout ends with a marker at Q3eR position

Geant4 model, luminosity side



- Bremsstrahlung photons are incident on 100 mrad Al exit window
- Non-converted photons are detected by the photon detector with graphite filter in front
- Conversion pairs are split in dipole magnet
- Electrons and positrons are detected in spectrometer detectors
- Photon detector provides instantaneous luminosity, spectrometer is aimed for precision measurement

Scattered electrons for low- Q^2 tagger studies

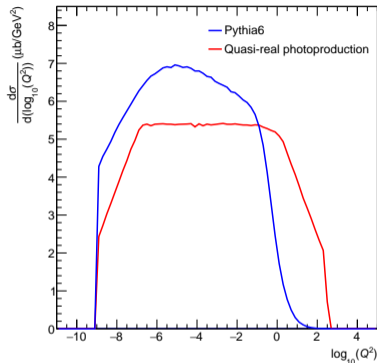


Figure: Cross section vs. Q^2

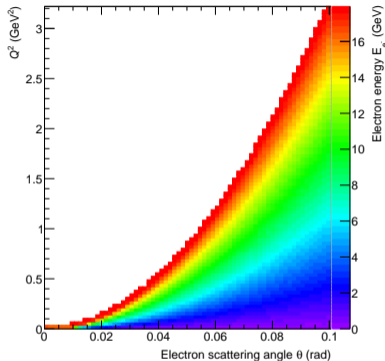


Figure: Q^2 , angle and energy

- Quasi-real generator is a part of [eic-lgen](#) following HERA approach in [Conf.Proc. C790402 \(1979\) 1-474](#)

- Input to Geant4 for taggers and ECAL, 18x275 GeV beams
- Total Pythia6 cross section is 54.7 μb
- Total quasi-real cross section is 53.8 μb
- Range in x and y for the quasi-real generator was set according to the Pythia6 sample

Angular and energy coverage for the taggers and ECAL

- Scattered electron energy and angle for events with a hit in one of the taggers and ECAL

Figure: Tagger 1

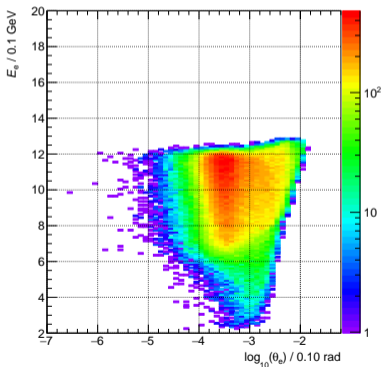


Figure: Tagger 2

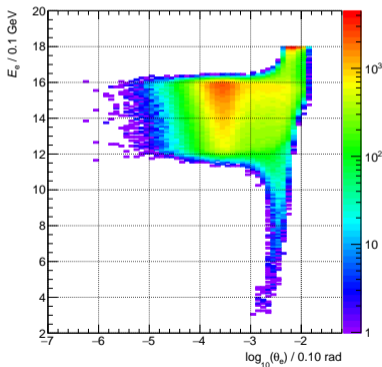
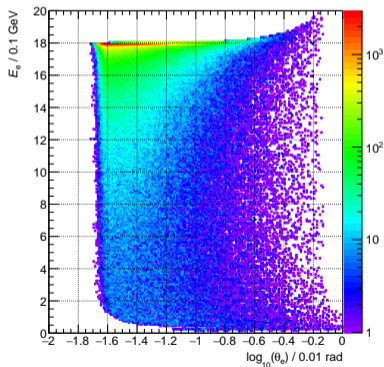


Figure: ECAL



Acceptance and coverage in Q^2

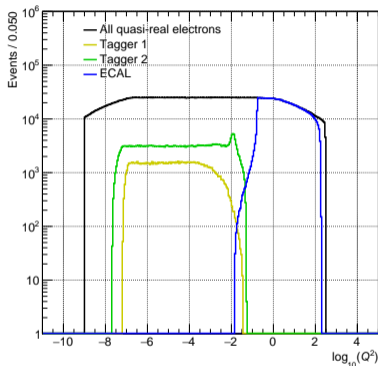


Figure: Individual detectors

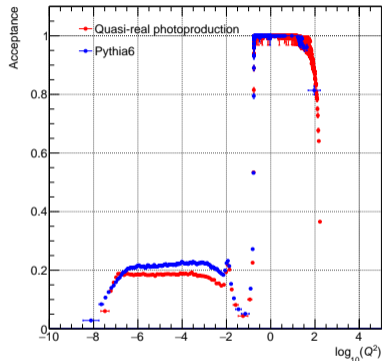


Figure: Overall acceptance

- Events with a hit in one of the taggers or in ECAL
- Acceptance is a fraction of events with a hit in least one of the detectors
- Dip around 0.1 GeV^2 strongly depends on available ECAL inner radius
- Acceptance is compatible with both event generators

Taggers and ECAL coverage in x , y and Q^2

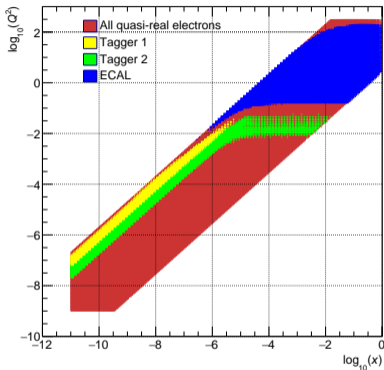


Figure: x and Q^2

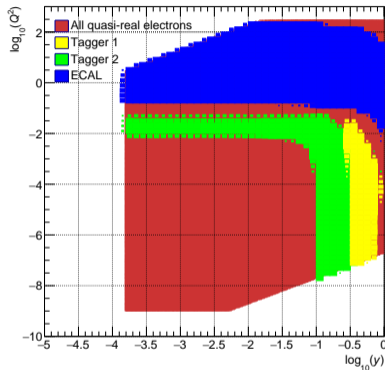


Figure: y and Q^2

- Red band gives all generated events
- Box diagrams show events with a hit in one of the taggers or in ECAL

Limits to possible Q^2 reconstruction due to angular divergence

- At one of previous far-forward detector meetings [here](#) I was showing a procedure to reconstruct electron scattering angle θ_e from its energy and hit position on the tagger
- The electron Q_e^2 is then given by the energy and scattering angle:

$$Q_e^2 = 2EE' (1 - \cos(\theta_e))$$

- The procedure worked to reconstruct the Q_e^2 down to $Q_e^2 \sim 10^{-5} \text{ GeV}^2$
- Relation between ideal true Q^2 and electron Q_e^2 is affected by beam angular divergence already at $Q^2 \sim 10^{-3} \text{ GeV}^2$

Effect of angular divergence to electron Q_e^2

Figure: With angular divergence

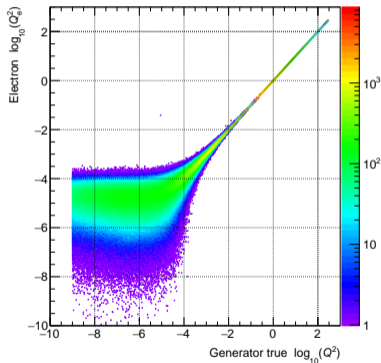
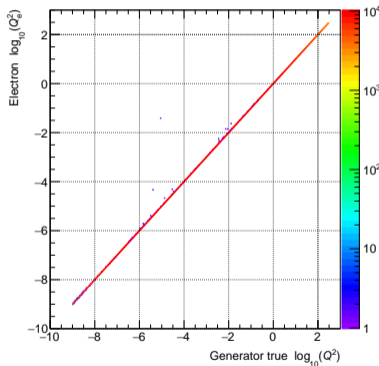


Figure: No divergence



- Electron Q_e^2 is proportional to the true Q^2 to 10^{-3} GeV^2
- At lower Q^2 the correspondence is lost
- When the divergence is removed, the Q_e^2 and Q^2 are identical

Possible resolution in Q^2 in presence of divergence

Figure: Tagger 1 and 2

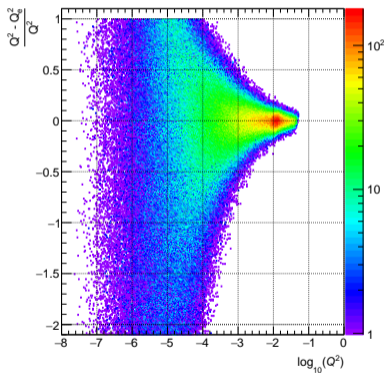
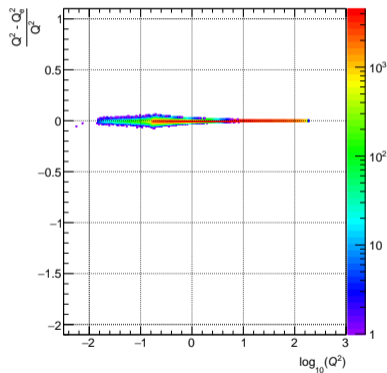


Figure: ECAL



- Relative difference between the electron Q_e^2 and true Q^2 :

$$\frac{Q^2 - Q_e^2}{Q^2}$$

- Shown as a function of true Q^2 for events with a hit in one of the taggers or in ECAL
- No issue for ECAL
- Strong limits to the taggers

Bethe-Heitler cross section for luminosity measurement

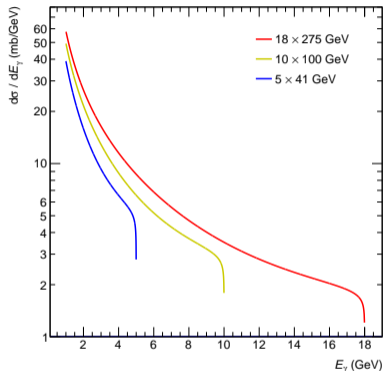


Figure: Bethe-Heitler cross section

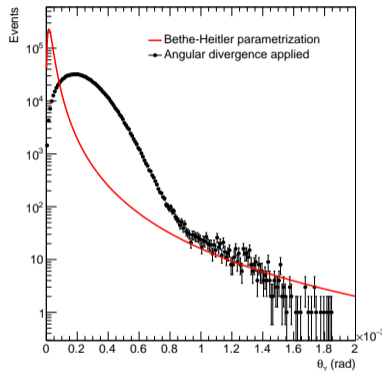
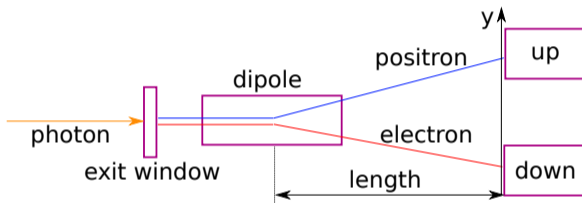


Figure: Angular distribution

- Cross section across all considered energies
- Angular distribution is shown for the top energy
- Divergence has a strong effect at small angles, compatible with HERA observation
- Input to Geant4 simulations

Geometry model for spectrometer acceptance



- Electron/positron gets transverse momentum from the dipole magnet,
 $p_T = \int B_x dz$
- Position y on the detector is given by the length l from magnet center to the detector and electron momentum p :

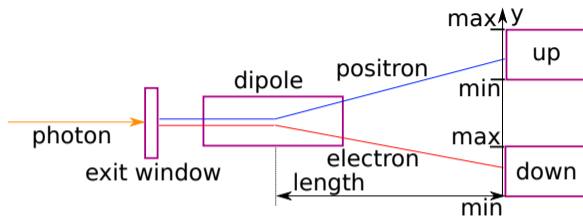
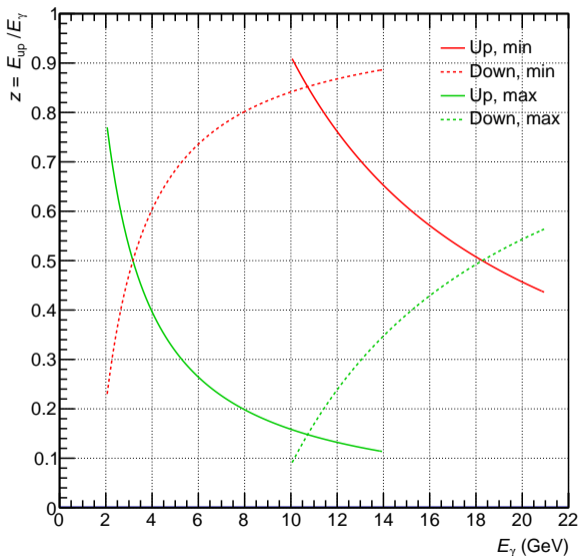
$$y = l \frac{p_T}{p}$$

- One electron in the pair has a fraction of photon energy $z = p/E_\gamma$
- The other has a fraction $1 - z$
- Positions of the pair arriving on up and down detectors y_{up} and y_{down} are given by z and E_γ :

$$zE_\gamma = \frac{lp_T}{y_{\text{up}}}, \quad (1 - z)E_\gamma = \frac{lp_T}{y_{\text{down}}} \quad (1)$$

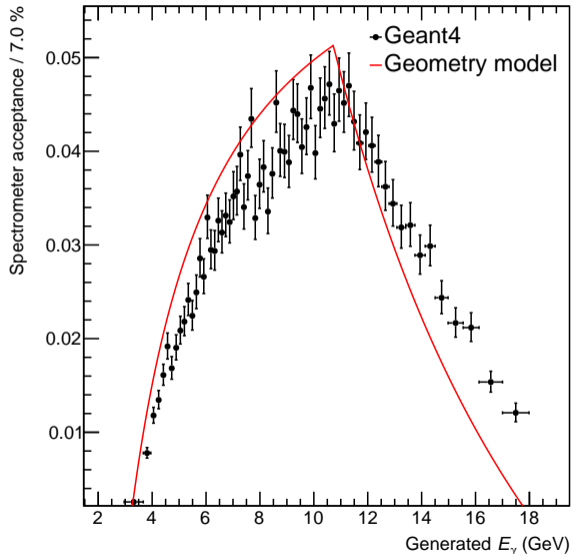
The approach shown here was used at ZEUS, [Nucl.Instrum.Meth. A565 \(2006\) 572-588](#)

Range of accepted y positions in spectrometer detectors



- Both up and down detectors have a minimum and maximum accepted y
- The figure shows z and E_γ at detector minima and maxima in y according to Eq. 1
- Photon is detected when electron and positron are within the accepted range in y , it is the enclosed area in the figure
- Spectrometer acceptance at a given E_γ is the range in z of the area

Spectrometer acceptance



- Simulation of 1M bremsstrahlung events, 18x275 GeV beams
- Acceptance is a fraction of events with at least 1 GeV in both up and down detector
- The model curve is application of Eq. 1 and min and max intervals from page 15
- Length of the magnet is 0.6 m, field is 0.26 T
- Detectors are spaced symmetrically at $y_{\min} = 42$ mm and $y_{\max} = 242$ mm
- Length from the magnet center to the detectors is 8.2 m
- Good agreement between Geant4 and the model

Light collection and timing in the model of PbWO_4 photon detector

- A model of 7x7 cells calorimeter was initially assumed for photon detector and spectrometer detectors
- Time shape of photoelectron signal will be shown in next pages
- The response is slow with respect to expected bunch rate

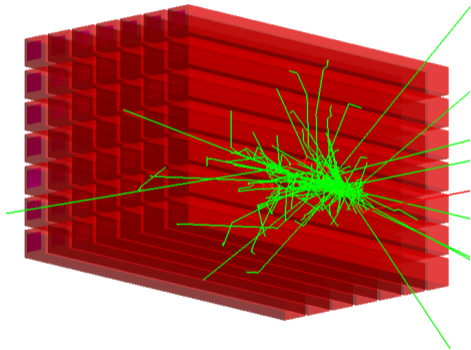


Figure: Photon in PbWO_4 calorimeter

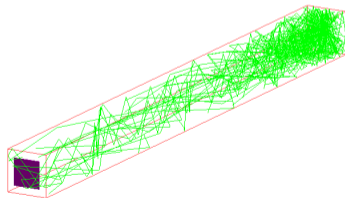
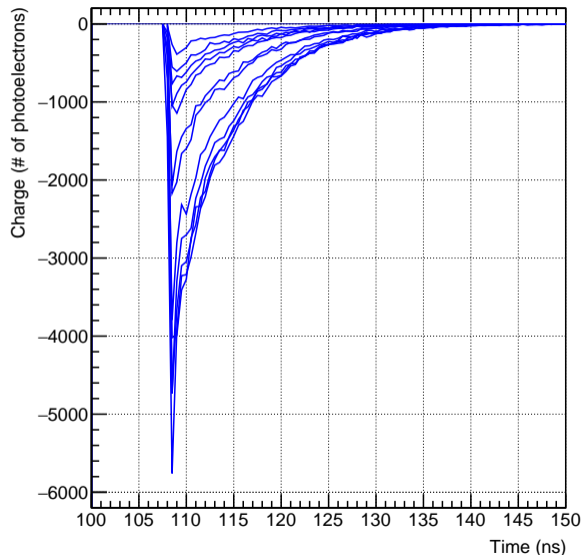


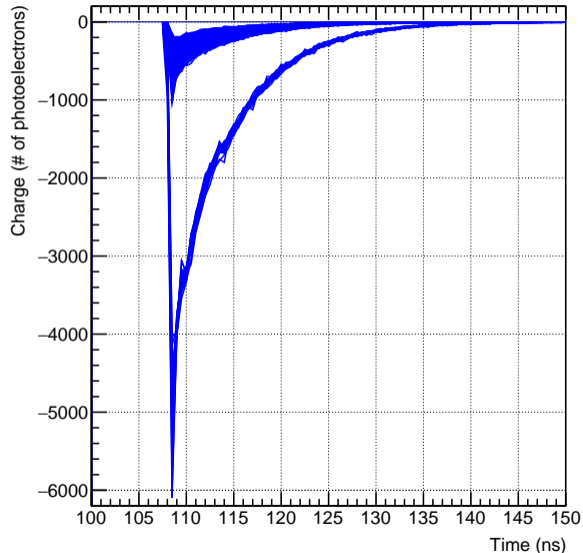
Figure: Light collection in calorimeter cell

Photoelectron pulses from a calorimeter cell



- Charge in number of photoelectrons created in the middle cell in 0.5 ns intervals
- Pulses of 12 consecutive events in Geant4 simulation of photons with uniform energies from 1 to 18 GeV
- An ideal scope would provide image like this
- Decay time depends weakly on pulse amplitude
- About 20 ns for all pulses to completely vanish
- Two times the bunch spacing at lower energies (11.2 ns), half at the top energy (44.8 ns)

Pulses for events with highest and lowest energies



- Signals from events with photons below 3 GeV or above 17.5 GeV
- The same simulation of 1k photons with uniform energies from 1 to 18 GeV as on previous page
- Confirms the conclusion that the decay time is too long with respect to bunch spacing

Possible calorimeter technologies

- Need to detect every single bunch crossing, signal has to leave the detector in $\lesssim 10$ ns
 - High radiation load due to beam proximity, high temperature due to synchrotron radiation
 - Similar demands hold for taggers and luminosity system, here is a list of some possibilities as a discussion input:
1. **Cherenkov** calorimeter, PbF_2 , [Nucl.Instrum.Meth.B 402 \(2017\) 256-262](#), BaYb_2F_8 , [Nucl.Instrum.Meth.A 317 \(1992\) 143-147](#)
 - Lead fluoride PbF_2 is in use for muon decay measurements
 - Heavy fluoride BaYb_2F_8 is radiation hard, was assumed for SSC
 2. **CVD diamond**, [IEEE Trans.Nucl.Sci. 56 \(2009\) 462-467](#)
 - Polycrystalline diamond is considered for ILC beam calorimeter
 3. **GEM** based calorimeter, [NSS/MIC 2009](#), [J.Phys.Conf.Ser. 404 \(2012\) 012031](#)
 - Gas as sensitive medium, ILC, CLIC
 4. **Silicon** sampling calorimeter, [JINST 12 \(2017\) 03, C03011](#), [JINST 15 \(2020\) 03, P03015](#)
 - HL-LHC upgrade

Summary

- Electron Q_e^2 stops to give the true Q^2 at very low Q^2 as a result of angular divergence
- Tagger and ECAL acceptance does not depend on generator choice
- Geometry model for luminosity spectrometer works as a fast approximation to the full simulation
- Response from PbWO_4 calorimeter cells would be too slow to separate single bunch crossings
- Next steps involve realistic beam layout, detector model, tracking for taggers and spectrometer and pileup effects
- IR drawing was created using *irview*: github.com/adamjaro/irview
- Quasi-real and luminosity generator is implemented here: github.com/adamjaro/eic-lgen
- Geant4 and analysis codes are here: github.com/adamjaro/lmon
- Pythia6 sample used with this study is here:
`/eicdata/eic0009/PYTHIA/ep/TXTFILES/pythia.ep.18x275.5Mevents.1.RadCor=0.Q2.all.txt`

Backup

Model of quasi-real photoproduction in eic-Igen

- Event generator implemented to eic-Igen using one photon exchange cross section from HERA study in [Conf.Proc. C790402 \(1979\) 1-474](#)
- The parametrization for quasi-real photoproduction in low- Q^2 approximation (Eq. II.6 in HERA study) is

$$\frac{d^2\sigma}{dx dy} = \frac{\alpha}{2\pi} \frac{1 + (1 - y)^2}{y} \sigma_{\gamma p}(ys) \frac{1 - x}{x} \text{ (mb)} \quad (2)$$

- The total photon-proton cross section $\sigma_{\gamma p}$ is used from Regge fit in [Phys.Lett. B296 \(1992\) 227-232](#):

$$\sigma_{\gamma p}(ys) = 0.0677(ys)^{0.0808} + 0.129(ys)^{-0.4525} \text{ (mb)} \quad (3)$$

- Equation 2, with input from Eq. 3, is used to generate values of Bjorken x and inelasticity y
- Kinematics is then applied to generate the electrons with output to ROOT, TX or Pythia6 format
- Similar procedure was used for H1 low- Q^2 tagger in [H1-04/93-287 \(1993\)](#)

Bremsstrahlung photons in eic-Igen based on Bethe-Heitler formula

- Bremsstrahlung photons and scattered electrons are generated using cross section as a function of photon energy E_γ and polar angle θ_γ
- Parametrization used at **ZEUS** is given in terms of electron and proton beam energy E_e and E_p

$$\frac{d\sigma}{dE_\gamma} = 4\alpha r_e^2 \frac{E'_e}{E_\gamma E_e} \left(\frac{E_e}{E'_e} + \frac{E'_e}{E_e} - \frac{2}{3} \right) \left(\ln \frac{4E_p E_e E'_e}{m_p m_e E_\gamma} - \frac{1}{2} \right) \quad (4)$$

- Scattered electron energy is constrained as $E'_e = E_e - E_\gamma$
- Equivalent parametrization from **H1** is in terms of $y = E_\gamma/E_e$ and center-of-mass energy s

$$\frac{d\sigma}{dy} = \frac{4\alpha r_e^2}{y} \left[1 + (1-y)^2 - \frac{2}{3}(1-y) \right] \left[\ln \frac{s(1-y)}{m_p m_e y} - \frac{1}{2} \right] \quad (5)$$

- Angular distribution of the photons is given in terms of angle θ_γ relative to electron beam

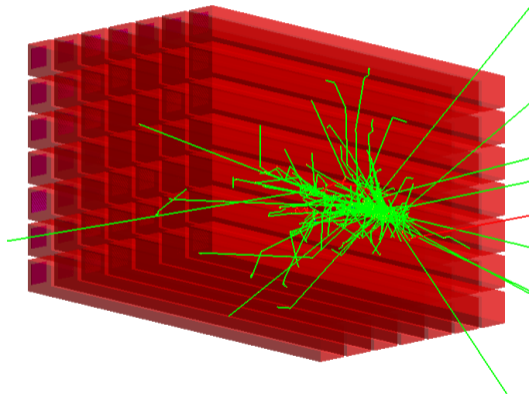
$$\frac{d\sigma}{d\theta_\gamma} \sim \frac{\theta_\gamma}{((m_e/E_e)^2 + \theta_\gamma^2)^2} \quad (6)$$

ZEUS: Eur.Phys.J. C71 (2011) 1574, **H1**: H1-04/93-287

Beam effects in eic-Igen event generator

- Vertex spread with Gaussian beam profile
 - ▶ Driven by emittance in x and y and bunch length in z
 - ▶ Vertex positions are generated from Gaussians in x , y and z of a given width $\sigma_{x,y,z}$
 - ▶ Using pCDR high acceptance configuration without hadron cooling for 18 x 275 GeV ep beams:
 - ▶ IP RMS beam size is $\sigma_x = 236 \mu\text{m}$ and $\sigma_y = 16.2 \mu\text{m}$, RMS bunch length is $\sigma_z = 1.7 \text{ cm}$
- Angular divergence
 - ▶ Separate for horizontal and vertical divergence
 - ▶ Implemented as Gaussian rotations of particle 3-momentum in x and y
 - ▶ The specific angles are generated with pCDR RMS values of $\sigma_{\theta,x} = 163 \mu\text{rad}$ and $\sigma_{\theta,y} = 202 \mu\text{rad}$
 - ▶ Improvement over the initial studies on luminosity monitor, where only a single σ_θ was used for Gaussian smearing of electron polar angles
- For Pythia6 events the beam effects are implemented with an afterburner approach on the scattered electrons

Model of photon detector



- Detects direct photons not converted on the exit window
- Calorimeter is composed of 7×7 PbWO_4 cells
- Each cell consists of 3×3 cm casing made of carbon fiber, 2 mm thick, holding the PbWO_4 crystal inside
- Length of each cell is 35 cm, same for casing and crystal
- Only the crystals, shown in red, are sensitive volume
- Response to a 1 GeV photon is shown on the plot

Optical properties and light detection in model of PbWO_4 crystal

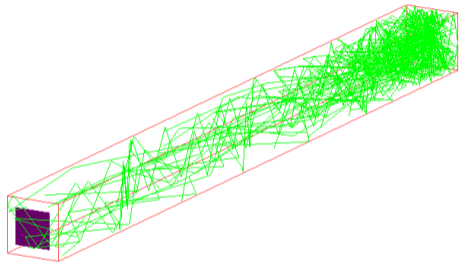
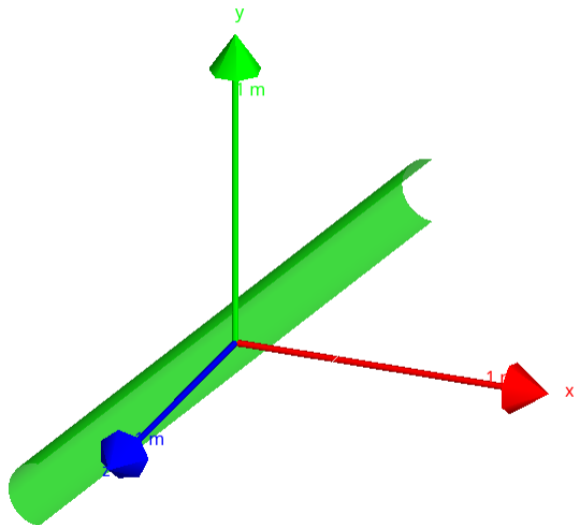


Figure: One calorimeter cell with 2 MeV deposition on the far side (facing the IP) and optical photon detector (magenta) on the opposite side. Optical photons are shown as green lines.

- Scintillation light yield is 200 per MeV with 6 ns decay constant (Knoll textbook)
- Wavelength 420 nm (peak of emission as measured for ALICE)
- Optical properties approximately according to ALICE TDR
 - ▶ Uniform across 350 - 800 nm
 - ▶ Refractive index 2.4, absorption length 200 cm
 - ▶ Reflectivity 0.8, efficiency 0.9
- Detection by PIN diode, magenta square in the drawing
 - ▶ Silicon of $17 \times 17 \text{ mm}^2$ area, $300 \text{ }\mu\text{m}$ thickness (following ALICE device)
 - ▶ Reflectivity of optical boundary from the crystal is 0.1
 - ▶ Quantum efficiency is 0.8
 - ▶ Detected photon creates one photoelectron of signal (after applying quantum efficiency)
 - ▶ Number of photoelectrons is the output of the detector

Model of exit window



- Layer of passive material to convert bremsstrahlung photons to e^+e^- pairs
- Also provides shielding against low energy synchrotron radiation
- Implemented as a half-cylinder of 1 mm thick aluminum, 10 cm radius and 100 mrad tilt along vertical y axis
- The tilt angle is motivated by synchrotron radiation studies